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VIRTUAL REALITY FEATURES OF FRAME OF REFERENCE AND DISPLAY DIMENSIONALITY WITH STEREOPSIS: THEIR EFFECTS ON SCIENTIFIC VISUALIZATION

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ABSTRACT

Initial discussion reviews the features of VR and their possible effects of scientific visualization performance. Three of these features: Dimensionality, stereopsis, and frame of reference are modified in an experiment that contrasted performance using a 2D display, and four displays varying in frame of reference (immersed vs. non-immersed) and in the presence of stereoscopic vision. Performance was measured across four separate scientific visualization subtasks: Search, Travel, Local judgment support, and Global judgment support. Participants were instructed to locate and follow a designated path through simple virtual environments and to answer questions about that environment. Subjects were divided into two groups varying in the type of frame of reference used; either an immersive or non-immersive. Each subject was to complete 5 trials in a 2D condition, 5 trials with their particular frame of reference presented in monoscopic vision, and 5 trials with their particular frame of reference presented in stereo. The results revealed that 2D performance was substantially worse than 3D performance across both frames of reference and stereo conditions. The results also indicate that the immersed frame of reference supported better travel performance, but severely hampered search and global judgment support. Stereoscopic vision slowed search performance and only enhanced travel using the non-immersed frame of reference. Local judgment accuracy benefited from stereo, but response time was unaffected. Global judgments showed no accuracy advantage from stereo, but did show faster responses when stereo was used.

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INTRODUCTION

The rapid increase in interest in visualization in both scientific and aviation contexts has led many to search for "the ultimate form" of visualization medium. Classical human factors rhetoric teaches that a well designed computer interface may provide the user with an effortless and efficient flow of communication to and from the specific device with which she or he interacts. While some 3D computer displays have been used to enhance the limited capabilities of the human information processing system, in aircraft separation tasks (Ellis, McGreevy, & Hitchcock, 1987) and in data visualization (Wickens, Merwin, & Lin 1994), others have interpreted "well designed" to necessarily mean advanced technology (Rheingold, 1991) and most recently Virtual Reality (VR) (Barfield & Furness, 1995; Durlach & Mavor, 1995). This has led to the debatable assumption that advanced (rather than properly integrated) technology invariably holds the key to successful application. Therefore, Virtual Reality's early notoriety may have come at the cost of it being significantly over-sold. VR may become a victim of its own good fortune as it leads to the use of features which may outstrip human performance when used improperly.

The goal for the research reported here will be to examine certain features of virtual reality in the task of data visualization. To do this we will examine the sub-tasks involved in scientific visualization; namely database navigation and support of correct judgments (local & global) about the data. However, before we can consider the possible costs and benefits of VR as a visualization tool, we first will look at the particular aspects which together comprise the technology of VR.

Introduction to Virtual Reality

The technology known as virtual reality (VR) or Virtual Environment displays (VEDs) is classified by Ellis (1994) as interactive, head referenced computer displays that give the users the illusion of displacement to another location (p. 17). The potential for VEDs lie in their ability to provide a new communication medium that might prove to be cheaper, more intuitive, and more efficient than former interface technologies. These features should evolve from the proper application of three types of hardware: (a) sensors, such as head position sensors, to detect the operator's body movements, (b) effectors, such as a stereoscopic display, to simulate the operator's senses, and (c) special purpose hardware that links the sensors and effectors to produce sensory experiences resembling those in a physical environment. Specifically these links will produce a sense of "virtual presence" (p. 18).

Features of VR

Wickens & Baker (1995) note that VR is not a unified phenomenon. It can be broken down into five separate analyzable features, each of which may have different effects on performance as they are individually added or removed. Wickens and Baker define the five elements of reality as 3 dimensionality, motion, interaction, an egocentric frame of reference, and multimodal interaction.

Dimensionality. This feature can be thought of as one which contrasts 3D (perspective and /or stereoscopic) viewing with 2D planar viewing. Wickens, Todd, and Seidler (1989) state that emerging technology in the areas of computer hardware (and software) and stereoscopic imaging technology, has led to displays that represent objects more naturally. That is, the displays more closely resemble the domain of objects and events they are to represent. This greater naturalism was thought to provide the viewer with a better understanding of the depicted structure or environment. For example a 3D geographic representation is more realistic than a 2D contour map. Furthermore, when an environment is examined from a distance of less than three to four meters, stereoscopic viewing can be used to produce a powerful depth cue. Therefore a 3D map with properly incorporated stereoscopic properties might be considered to be the most realistic of all three maps. VR technology typically incorporates both elements of the naturalistic perspective, namely 3D perspective with stereoscopic viewing.

Motion. The motion feature contrasts static vs. dynamic displays. The environment in which humans evolved is very dynamic, therefore a moving representation of the world is more "real" than is a series of static "snap shots." As with the issue of dimensionality, advances in computer technology have increased the speed of computer graphic capabilities, thus increasing the ability of a display to accurately represent a dynamic world. VR relies heavily on motion in its applications, and has (despite recent advances) been severely limited in its abilities to provide rapid "real time" motion simulating the visual experience of a user moving through an environment. (Smets & Overbeeke 1995).

Interactivity. This feature characterizes how the user interacts with the environment. VR interaction is characterized by an interactive closed loop mode (user centered) rather than open loop mode (limited or no feedback). A more realistic closed loop mode is one in which the learner has control over what aspect of the virtual environment is viewed or visited. In this sense the user would not be relegated to the role of passive observer, but would rather be an active explorer or navigator in the environment. VR incorporates a user centered mode of interaction. This allows the user to act on or explore the environment as she or he sees fit.

Frame of reference. This aspect represents the frame of reference (FOR) with which the user "sees" or observers the environment. Two of the possibilities

are an inside-out (egocentric or immersed) and an outside-in FOR (exocentric or non-immersed). The immersed perspective is more realistic because it incorporates a vantage point from the view point of the user (that is the device in the environment being controlled by the user). For example, an exploration vehicle could be controlled with an immersed display which would have a perspective similar to that taken from a camera attached to the front of the vehicle. If a non-immersed display was used, the perspective would resemble one taken from a camera stationed above or behind the environment. The camera's view would incorporate the entire environment (or a much larger portion than is available in the immersed display). Therefore, not only would the objects in the environment be visible but the representation of the user's exploration vehicle would be visible as well. The exocentric perspective could be from a camera fixed in a single direction (i.e., fixed north-up) or from a camera mounted behind the user (i.e., on a tether), following behind the vehicle's track. VR uses the immersed perspective to represent the environment. Thus operators of VR technology experience the frame of reference as if they were actually inside the environment.

Multimodal interaction. There are a great variety of input devices available to manipulate the virtual environment. Some of the possibilities include speech recognition and gesture sensation, whether captured by camera or sensed through a "data glove" (Zimmerman & Lanier, 1987). Equally, there are a number of feedback sources available to enhance the user's experience of the virtual environment. Body motion through an virtual environment can generate proprioceptive or kinesthetic feedback to the users. Tactile feedback is available to provide feedback when users encounter "objects" of varying textures within the virtual environment (Minsky & Ouh-Young, 1990). Force feedback can be delivered through a joystick or other hand grips (Brooks & Ouh-Young, 1990). Auditory feedback can be generated through the use of 3D localized sound (Begault & Wenzel, 1992), and feedback from head position can alter the view of the environment that is seen. These interaction and feedback techniques are more similar to the way we interact with our normal world than are the traditional input devices of keyboards and mice.

Mediating Factors on VR Aspects

Wickens and Baker (1995) note that some of these five elements are not independent and will often interact with one another. For example, performance differences due to changes in frame of reference will definitely depend on whether the display is dynamic or fixed. Each of the previously mentioned components will produce not only its own effect but also may interact with other components.

Furthermore, the influence of a feature may be very much task dependent. Therefore, factors that are found to enhance performance in one task may be found to hinder performance in another task. As one example, Wickens and Prevett (1995) examined the effects of varying the level of display egocentrism (immersed)

and exocentrism (non-immersed) on a navigational tracking task and on tasks that assessed the user's knowledge of object location within the environment. They found that an immersed display produced better vertical and horizontal navigation than the non-immersed and planar displays in the navigation task. However, when analyzing location awareness performance, they found that the non-immersed displays supported performance that was substantially more accurate than that supported by the immersed displays.

Based on these mediating factors, Wickens and Baker (1995) suggest an analysis be carried out comparing the possible benefits of adding these components of reality, with their potential costs. Most of these features will necessitate significant financial requirements, increases in system complexity, unreliability, and maintenance problems. In terms of possible benefits, one of the purposes of this report is to establish whether adding a particular feature of reality has any benefit to performance at all. For the purposes of this study we will examine the particular benefits of three aspects of VR, namely Dimensionality (whether a 3D data set should be presented as a 3D volume or 2D co-planar displays), stereoscopic augmentation, and frame of reference (Immersion vs. fixed view exocentrism). These aspects will be examined across four different conditions as they influence a set of component tasks frequently employed in scientific visualization.

VR Applications Examined in the Present Study

Much of the interest in VR has centered on its possibilities to enhance scientific visualization by facilitating data navigation and supporting accurate data judgments. It is possible to imagine a scientist who would use VR as a tool to examine a particular multidimensional (greater than 2 dimensions) environment. For example consider the scientist, analyzing the distribution of toxic concentrations based upon geographic location (X & Z dimension) as well as depth (Y dimension). The scientist may find it necessary to "zoom in" and examine a particular concentration as well as "zoom out" to gain a more holistic understanding of the distribution of toxic concentrations in terms of their overall location, patterns, shape, etc.

For the purposes of this experiment we will consider scientific visualization as a dual component process: Database navigation and Judgment support. Database navigation can be further divided into two subtasks: Search and travel. The search subtask is triggered by the user's need to locate an object of interest in the virtual environment. This could correspond to our scientist's desire to locate a particular concentration to examine. It could also be applied to locating a potential aircraft conflict in a virtual ATC environment, an object representing a reference in a data base (Newby, 1992), an item in a menu (Jacoby & Ellis, 1992), a fact in a hypertext space (Golovchinsky & Chignell, 1993), a particular data point in a scientific data base (Wickens, Merwin, & Lin, 1994) or a tumor in a representation

of body tissue (Abarbanel, Friedhoff, Langridge, Pearlman, & Star 1993). The common element between these studies is that all of these tasks require a visual search of an unknown environment for some designated "target." Once the object is discovered visually, there may also be a need to orient the VR device on a course toward the object, so that travel may take place.

The travel subtask is triggered by the user's need to navigate quickly and accurately throughout the virtual environment (VE) to attain a closer (zoom in) view of a certain object. Because VEs are not necessarily tied to the natural physical laws, travel through VEs can be instantaneous. While this may increase the actual speed and flexibility of the navigation process, it may have severe consequences in terms of situational awareness. Warren and Wertheim (1990) suggest that locomotion through a virtual environment should capitalize as much as possible on the user's own natural navigation experiences. Based on this suggestion we would not desire to have instantaneous motion within our environment because operators are not used to navigating that way. Furthermore, Wickens and Baker (1995) suggest that virtual travel should represent a compromise between two features; speed and situational awareness, the latter of which may be lost with rapid travel speeds. Loss of situational awareness is a major concern in the aviation community (Billings, 1991; Wiener, 1989), and it is also a potential concern in terms of how it degrades scientific visualization performance. Therefore, for purposes of this experiment, travel throughout the VE was not designed to be instantaneous.

Regarding the judgment task, this report considered two subtasks: Local (relative) judgments and Global (integrative) judgments. Local judgments can be characterized by how well the displayed information facilitates the user's evaluation of an object's position. This position can also be characterized either as relative (in relation to other objects) or as absolute (i.e., measured along a single scale), such as individually measuring heat, volume, depth, etc.). Due to the large number of possible absolute scales and the specific nature of these scales, this experiment focused on only the relative judgment support.

Global judgments can be thought of as measures of the viewer's ability to grasp the environment as a whole. For example can the viewer meaningfully understand the distribution, shape or size of the environment that she or he just encountered? This is the goal of many scientific visualization applications of VR and therefore will be examined in this report. Specifically, we will measure global judgment by the viewer's accuracy in describing the distribution or shape of objects within the VE.

REVIEW OF THE LITERATURE

In the following pages, we now review the literature which has examined the three features investigated here on the performance of the scientific visualization subtasks described in the Introduction.

Dimensionality and/or Stereo (D&S) Effects on the Visualization Subtasks

In the following section, we will focus on how 3D and stereo viewing conditions were found to affect the visualization subtasks addressed in this experiment: Search, Travel, Local Judgment Support, & Global Judgment Support.

D&S effects on search. While little experimental data exist on how dimensionality and stereoscopic viewing affect the search task, an intuitive example will provide some guidance. First, we must clarify that the search task is actually composed of two separate subtasks; target location and icon orientation. Target location can be defined as the time and/or effort required by the subject to find the target (i.e., flashing box, colored symbol, etc.). The salience of the target, relative to the background, will be the biggest determining factor in this "finding" task. Therefore if all factors affecting salience (i.e., target luminance, viewing distance, background noise, etc.) are held constant on all displays, then we should expect little difference between the 2D and the 3D formats.

The icon orientation subtask requires the user to position her or his icon on a trajectory that will intercept the target, which is already in sight. To properly align the icon, the subject must have a clear picture of both "where they are now" and "where they need to go." Intuitively, the integrated 3D display should show an advantage for this task. With all three dimensions integrated into one display, the user only has to attend to the one display. The planar 2D displays will require a division of visual attention between two panels (i.e., scanning). Added to this, the 3D display removes the need for mental integration between the two separated screens of the 2D display.

Ellis, McGreevy, and Hitchcock (1987) compared plan views (top down 2D representation) vs. perspective views (3D representation) of air traffic displays in an air traffic avoidance task. They found an approximate 10% time reduction for interpretation of the perspective display. In similar work, Bemis, Leeds and Winer (1988) found 3D perspective displays revealed a substantial advantage over 2D planar displays in an airborne threat identification (i.e., search) and interception coordination task.

Liang, Wickens, and Olmos (1995) explored the effect of display dimensionality on tasks involving the estimation of an absolute bearing toward

terrain features; a task similar to "icon orientation." The results showed that 3D displays supported significantly faster response times than 2D displays for absolute bearing judgments. These studies cite the reduction of scan time as significant contributors to the success of the 3D displays relative to the 2D displays. Therefore, it seems the 3D display supports better search performance by eliminating the scan between displays.

If 3D viewing is advantageous for some aspects of the search task, it might be anticipated that enhancing the sense of 3D by means of stereoscopic viewing would provide further performance enhancement. Several studies have shown a stereopsis benefit for the performance of such tasks as simulated rotorcraft performance (Parish & Williams; 1990) and neurosurgery (Sollenberger & Milgram, 1989). Specific to a search task, Zenyuh, Reising, Walchli, and Biers (1988) compared the relative abilities of a stereoscopic 3D display versus a conventional 2D display to support the task of searching spatial quadrants for targets in a simulated air to air combat display. Zenyuh, et al. found greater accuracy for the 3D stereoscopic display relative to the 2D display. Response time was not significantly different between the two display formats. Way (1988) investigated whether stereo would enhance performance in the detection of malfunctions of a simulated engine system. Way found that stereoscopic viewing used with a color code resulted in fewer errors than a 3D display with the color code alone, although it did not reduce response time. However when stereo was used alone, a significant increase in response time was found relative to the conditions featuring only color code and color code combined with stereo. Hence we might conclude that the benefits of stereo to search are ambivalent, and probably depend a good deal on what is being searched for and the relative salience of other cues in discriminating the target from the background.

<u>D&S effects on travel.</u> One of the major selling points of VR technology is that it allows for a deeper exploration of the database by allowing the viewer to "zoom in" toward a particular point of data. This exploration is assumed to facilitate a better appreciation of the relation between variables than can be achieved by separated 2D displays. However, this exploration requires the viewer to have the ability to travel through the database. Therefore, research discussing travel and its relation to dimensionality and stereoscopic viewing is important to this study.

When defining the traveling subtask for this experiment, we must consider both the cognitive elements (How well can viewers avoid getting lost in the virtual space?) and the perceptual-motor (i.e., tracking) elements (How well can viewers control the viewpoint in virtual space?). The specific methodology of the experiment guards against the cognitive concerns; making motor control our chief concern. Haskell and Wickens (1993) found that 3D displays led to superior control in the lateral and vertical axes along the flight path during a landing approach in a simulated aircraft, an effect replicated by Wickens and Prevett

(1995). However, the 2D display was shown to have superior performance in terms of controlling airspeed. The advantage for 3D was attributed to the reduced scanning with the integrative displays, while the cost of the 3D display for speed control was attributed to the fact that 3d displays are typically ambiguous in representing distance along the viewing axis (line of sight ambiguity).

Wickens, Liang, Prevett, and Olmos (1994) also compared 2D and 3D displays to examine their effects on navigation performance. The results indicated no significant difference between the 3D and 2D perspectives in terms of lateral tracking performance. Furthermore, they noted some 3D costs in vertical tracking performance. However these costs were small, and the results showed a trend toward 3D cost reduction with practice.

Wickens and Prevett (1995), using a similar paradigm as Haskell and Wickens (1993), found that an exocentric (non-immersed) 3D display was no better than the 2D display in navigation tasks. As did Haskell and Wickens, they concluded that the exocentric view produces ambiguity along the line of sight.

The augmentation provided by adding stereo to 3D displays has also been examined in some 3D navigational tasks. The field of telerobotics provides a natural testing ground for examining the possible benefits of using stereo. Most of the actual environments encountered by teleoperators are 3D volumes, which require efficient user feedback and a spatially orientated interface to promote successful exploration. Pepper, Smith, and Cole (1981) and Pepper, Cole, Spain, and Sigurdson (1983), found that stereoscopic viewing provided better tracking performance, but that the advantage was mediated by visibility, task type, and learning factors. Stereoscopic viewing had a greater advantage over monoscopic viewing when scene complexity was increased and object visibility was decreased. In a related study, Cole, Merrit, Coleman, and Ikehara (1991) required subjects to guide a remote operator through a wire maze. When subjects used a stereoscopic display they completed the task faster and with higher accuracy than with a monoscopic display. Furthermore, Cole et al. found that subjects explored the wire maze in a slow trial and error fashion when using the monoscopic display, but not when using the stereoscopic display. This suggests that the stereoscopic display gave the subjects a better idea of the spatial characteristics of the maze than the monoscopic display.

Drasic (1991) found similar stereoscopic benefits in reducing response latencies and execution time in a teleoperation task. Furthermore, Drasic found that stereoscopic viewing reduced both the time required for training and the error rates.

Stereoscopic displays have also been examined in non-teleoperation tasks. For example, monoscopic and stereoscopic displays have been compared with regard to how they affected performance on a three-axis manual tracking tasks

(Ellis, Kim, Tyler, McGreevy, & Stark, 1985; Kim, Ellis, Tyler, Hannaford, & Stark, 1987). These studies found that stereoscopic 3D displays supported smaller tracking errors than did their 3D monoscopic counterparts. Furthermore, Sollenberger and Milgram (1993) replicated these studies and found that stereoscopic displays produced substantial benefits in performance in a 3D path-tracing task. Nataupsky and Crittenden (1988) however, observed few benefits of stereo in flight path tracking when pilots viewed a 3D "highway in the sky", given the presence of other rich depth cues.

Summarizing these experiments, it seems that stereoscopic displays generally support better navigation performance. Much like the superior navigation performance of 3D over 2D, we can assume that stereo superiority is due to its ability to present a heightened sense of perspective parallel to the viewing axis, often needed by the user and often poorly supported by other depth cues.

D&S effects on local judgments. Several studies have examined whether the use of a perspective displays may support more accurate judgments of spatial information than would be found using planar (2D) displays. Burnett and Barfield (1991) found that a 3D display of a simulated air traffic environment resulted in more accurate recall of an aircraft's position compared with performance using a planar display. While these results may seem encouraging for supporting the idea that 3D will led to better local judgment performance, other studies have arrived at different conclusions.

Wickens and Todd (1990) found that on tasks requiring the relative judgment of position across a single dimension, no significant difference existed between a 2D (bar graph) display and a 3D integrated display. However, they found a shorter response latency for the 2D display. Wickens and May (1994) contrasted how 2D vs. 3D displays would affect the subjects' abilities to judge aircraft trajectory relative to mountainous terrain. Wickens and May found that air traffic controller subjects were less accurate with the 3D display than with the 2D display in judging complex 3D trajectories. Pilot subjects in contrast showed no significant difference between display types.

Wickens, Liang, Prevett, and Olmos (1994) found that the pilot's ability to indicate the relative vertical position of a given navigational feature was superior in the 2D format, while the 3D display format supported faster response times. Wickens and Prevett (1995) used a similar paradigm and found that there was no significant difference in response time to local judgment questions. However, there was a significant advantage in accuracy for the 2D displays.

Many of the these studies state that relative accuracy may be degraded in 3D displays due to line-of-sight ambiguities. Furthermore, they propose that the shortened response latency of the 3D displays was due to the elimination of

scanning between two planar displays. According to these studies, there may be a disadvantage to using 3D displays for local judgments inside complex 3D environments.

However, when 2D and 3D displays were compared in a scientific visualization task, the results were somewhat different. Wickens, Merwin, and Lin (1994) varied display dimensionality to examine possible techniques to assist scientists in evaluating multidimensional data. Subjects viewed a series of complex 3D data sets, from which a set of discrete points or observations were sampled. In one experiment, subjects viewed complex data sets in both 3D and 2D displays and answered "on-line" questions about the relative values of displayed information. They found that 2D displays were responded to more slowly than 3D displays. Furthermore, they found that on questions requiring integration of information, the 3D displays were responded to more accurately than the 2D displays. Based upon this work it seems that 3D displays should be the recommendation to those interested in making local judgments within scientific visualization contexts. However, other viewing parameters known to heighten the realism of the display, notably stereoscopic viewing, must also be considered.

In this regard, Yeh and Silverstein (1992) found that the addition of binocular disparity to a perspective display led to faster and more accurate judgments of altitude and depth of objects in a 3D volume than was accomplished with a perspective display alone. In a similar study, Barfield and Rosenberg (1995) found that stereoscopic displays resulted in more accurate estimates of elevation angle between two subjects, while no benefit was found in estimating azimuth. Wickens, Merwin, and Lin (1994) also varied the presence of stereo in their experiment. Stereo views of the 3D display were found to support better local judgment performance above than that found in monoscopic 3D displays.

Based upon the results of these experiments, we can see that the use of stereoscopic viewing does increase the accuracy of relative judgments. These advantages suggest that 3D displays combined with stereo will achieve superior accuracy to 2D planar displays.

D&S effects on global judgments. Much of the previous research on global judgments regarding the structure of the database comes from examination of dimensionality and its effects on global situational awareness in aviation. Rate and Wickens (1993) examined global judgment support, while pilots flew a simulated approach task and found that assessments of the pilot's ability to spatially localize terrain features was better with the use of 2D displays. Furthermore, the results indicated that pilots showed no time advantage for the 3D display.

Wickens, Liang, Prevett, and Olmos (1994) used two measures to assess dimensionality effects on global judgments; a frozen screen test and a map reconstruction test. The frozen screen test halted the task temporarily and pilots

were asked questions referring to the global aspects of the environment (i.e., the shape of certain terrain features or altitude and heading changes necessary to intercept an object). The map reconstruction task, given after completion of the final landing task, required the pilots to draw as many terrain features as they could remember encountering and to indicate the direction of north. They found that on the frozen screen tests, the 2D displays supported faster response times fro the pilot to detect a collision given a specific altitude and heading change. Furthermore, the 2D displays supported more accurate placement of terrain features for the map drawing task than did the perspective 3D display. As with the other "aviation studies" (Wickens & May, 1994; Wickens & Prevett, 1995), Wickens et al. speculated that 3D displays' accuracy may be degraded due to line-of-sight ambiguities.

In their examination of visualization of a 3D database, Wickens, Merwin, and Lin (1994) as noted above, found that "on line" questions requiring the most integration (global judgments) were better supported by 3D displays rather than 2D displays. Further more they tested subjects for their retention of the surface characteristics, after a number of samples were viewed from each surface. This was assessed by a written post-test which asked them to provide detailed knowledge of the data base (i.e., shape formed by the data points and values of the variables at specific regions of the data space). The first experiment compared 3D vs. 2D displays on the post-test and revealed no significant differences in global judgments. In a second experiment, Wickens, Merwin and Lin (1994) found that stereoscopic viewing facilitated better performance on the global "on line" questions than 3D monoscopic viewing, but that stereo had no benefit on the long term memory for the structure of the database.

While most of the studies suggest that there is no clear global judgment advantage for one type of dimensionality (3D or 2D), the work of Wickens, Merwin and Lin (1994), suggests otherwise. Furthermore, this latter work is the most related to the present study and the field of scientific visualization. Therefore, we speculate that 3D displays should surpass 2D displays in terms of supporting global judgments of the structure of the data. Furthermore, as noted in Wickens, Merwin ,and Lin, stereoscopic viewing should not improve global judgments.

Frame of Reference (FOR) Effects on the Visualization Subtasks

Previous studies do not support a single "best" display with respect to dimensionality and stereo. Despite this inconclusiveness, it has been suggested that because humans interact with their world in terms of three dimensions, the optimal interface should resemble that environment as closely as possible. In terms of VR, this would mean the immersive perspective of VR, representing the highest level of realism to the subject, should allow for the most efficient interface.

However, we must remember that "optimal performance" and "optimal reality" are not necessarily the same and it is the former that is the goal of these interfaces.

Therefore in the following section, we will examine research addressing the effects of modifying the frame of reference (FOR) in the 4 visualization subtasks addressed in this experiment; Search, Travel, Local Judgment Support, & Global Judgment Support.

<u>FOR and search.</u> As is common with VR research, there is a shortage of empirical studies which addresses the issue of frame of reference and its effect on search performance. As stated earlier, the search task actually is comprised of two subtasks; target location and icon orientation. In our comparison of 2D vs. 3D displays, the two sub-tasks could be addressed separately. However when considering frame of reference, it will be impossible to separate the two tasks at certain times. An example of this can be found when an egocentric (immersed) FOR is used. Due to the fact that the viewing perspective is depicted from the front of the icon itself, orienting the icon toward the target is the only way the user can locate the next target hence location and orientation are accomplished in parallel. On the other hand, the exocentric (non-immersed) FOR will require that the two subtasks be addressed separately. The detached "birds-eye" viewpoint will allow the viewer to survey the entire database visually, without "actively" locating the next target via manual manipulation. The viewer will locate the target by visual search and will then proceed directly with the manual orientation task.

The immersed egocentric viewpoints are limited in this sense by their "key hole" views because the viewpoint will only allow the viewer to search the field of view that she or he can see through the "key hole" at that time. This keyhole view can be expanded, by enlarging the geometric field of view (GFOV) thus increasing the user's view of the data, (Kim, Ellis, Tyler, Hannaford, & Stark, 1987; Wickens & Prevett, 1995). However, increasing the GFOV may result in "nonecological" distortions which could hinder local judgments (McGreevy & Ellis, 1986). Therefore, in the experiment we reported below the GFOV was not expanded, thus resulting in a limited key hole view for the immersed FOR condition. Based upon this line of thinking, it seems that the unrestricted field of view inherent in the non-immersed FOR should support better search performance.

<u>FOR and travel.</u> Several studies have examined the effects that an egocentric vs. and exocentric FOR would have on aircraft flight. In these studies, the contrast of reference frames, has been varied in two different comparisons; immersion vs. exocentric, and rotation vs. fixed. Both comparisons deal with comparing a more egocentric vs. a more exocentric viewpoint. The more egocentric FORs would include viewing the environment as a pilot would (immersive viewing) or using a rotating map that corresponds to the pilot's outside view. The exocentric FORs would include viewing the environment as a viewer would if detached from the vehicle (non-immersed) or using a map fixed in a

certain (typically north-up) direction. Rate and Wickens (1993) compared performance for pilots on a landing task using either a rotating track-up or a fixed north-up displays and found that the track-up (egocentric) displays were better for lateral flight control. These results were replicated by both Wickens, Liang, Prevett, and Olmos (1994) and by Liang, Olmos, and Wickens (1995), who found that more exocentric (fixed) maps produced larger deviations in both lateral and vertical dimensions than did egocentric maps.

Wickens and Prevett (1995) examined the effects of varying degrees of exocentrism on tracking performance. Exocentricity was varied by adjusting the distance (tether length) which the viewpoint was positioned away from the aircraft (i.e., the degree of "immersion"). The results revealed that the fully immersive FOR supported better tracking performance in both the vertical and horizontal axes than either the planar or exocentric perspective displays. Using a similar paradigm, Barfield, Rosenberg, and Furness (1995) found the least exocentric (full immersive) display supported the lowest tracking error and quickest time to reach a target.

Further research was conducted using the "Tunnel in the Sky" primary flight display. The tunnel in the sky is a perspective display which functions much like a flight director, but provides a look-ahead capability and basic ground reference elements. It also uses an immersed (egocentric) frame of reference. The tunnel in the sky system has been found to enhance performance relative to a non-immersive display on simulated three dimensional helicopter approaches (Grunwald, Robertson, & Hatfield; 1981).

Related research was performed by McGovern (1993) who studied accidents involving teleoperated vehicles at the Sandia National Laboratories (SNL). Subjects in the immersed group controlled remotely operated vehicles equipped with direct video and audio feedback. Subjects in the non-immersed group had no such links and was forced to operate the vehicles from a fixed position. The operators remotely navigated the vehicles through an off-road track. Nine of the ten accidents which occurred in the "immersive group" involved a loss of control due to a miscalculation of the vehicles' dynamics (e.g., hitting a bump or turning too fast) (p. 186). The non-immersive group had a similar number of accidents, however those accidents involved underestimating stopping distances (hitting a fence), problems with depth perception (hitting a tree and a post), and control reversals (hitting a car). This suggests that the non-immersive group's problems involved misunderstanding the environment within which they were operating. Therefore, non-immersive frames of reference seems to cause confusion to the navigate about the nature of the environment and her or his place inside it.

Summarizing these results, we find that egocentric FOR, whether achieved by map rotation or by immersion of the viewpoint, produces better tracking

performance. Based on these experiments, we expect the immersive display to support superior travel performance relative to both the non-immersed 3D display and the planar 2D display.

FOR and local judgments. Several experiments have examined how FOR affects relative judgment performance. Barfield and Kim (1991) varied FOR by altering the GFOV and the tether lengths of the subjects' viewpoint and found that a mid-exocentric FOR produced the lowest azimuth error of estimation of target location, but the greatest errors in elevation judgment. Using a similar paradigm, Wickens and Prevett (1995) varied degrees of exocentricity (via their tether lengths) and found no difference in response time, but that increasing exocentricity generally led to higher accuracy in relative judgments of target location. The trend for accuracy was reversed when an extreme exocentric viewpoint was used; resulting in lower accuracy than a mid-exocentric point of view.

Wickens, Liang, Prevett, and Olmos (1994) had pilots report the relative bearing of a terrain feature and judge whether it was above or below the simulated aircraft. Pilots flew with either fixed north-up maps (exocentric) or rotating maps (egocentric). There were no significant differences between the two map types in above/below judgment accuracy, while the fixed north-up map supported more accurate estimates of relative bearing and produced faster reaction times than the rotating map. Using the same fixed vs. north-up paradigm, Liang, Wickens and Olmos (1995) assessed performance on a task which required pilots to report an absolute bearing upon which they plane would fly to intercept an unexpected target. Liang et al. found no difference in response time or judgment accuracy between the two map display types.

After reviewing these studies, it is still unclear whether increasing the degree of exocentricity of the display will improve local judgment task performance. Therefore further work, such as that which we report in this experiment, must be done to see how different FOR will affect relative judgment support.

FOR and global judgments. Aretz (1991) examined the performance differences between a track-up map and a fixed north-up map on a map reconstruction task. The task required the subject to place landmarks, encountered in flight simulation, in their appropriate locations after completion of the flying task. The results indicated that more landmarks were recalled in their correct locations with the north-up (exocentric) displays.

In a similar study, Wickens et al. (1994) examined differences in global judgments between north-up vs. track-up maps. Specifically they examined the FOR affects in the same ways as they examined the dimensionality affects. Additionally, a map reconstruction task was given to the subjects after the final landing task had been completed. They found that pilots had quicker response

times when using the track-up (immersed) display for the frozen screen tests. However there was no difference in accuracy between the two displays. The results of Wickens et al. replicated the findings of Aretz (1991) by finding a significant advantage for the north-up (non-immersed) display in the map reconstruction task.

Further replication was provided by a study by Williams, Hutchinson, and Wickens (1994) who examined how fixed versus rotating frames of reference used during training would influence later recall of the terrain's configuration. Williams et al. categorized participants in terms of how they held the map during training; finding that 60% of the subjects consistently held the map north-up and that 28% rotated. Assuring that the distribution of map orientation preference was uniform, Williams et al. evaluated pilots on a map reconstruction task (similar to that used by Aretz, 1991; Wickens et al., 1994) and found that the north-up (exocentric) map participants had significantly higher map reconstruction scores that their track-up (egocentric) map counterparts. It should be noted, however, that the advantage of north up versus track up maps for terrain recall has not always been found (Liang et al., 1995).

Finally, in the experiment described above, Wickens and Prevett (1995) investigated how varying exocentricity - via tether length would affect global judgments. Using the same map reconstruction task, they found no significant difference between the displays using the varying degrees of exocentricity. Barfield, Rosenberg, and Furness (1995) compared immersed (egocentric) and non-immersed (exocentric) displays and found that pilots flying with an exocentric frame of reference yielded better map reconstruction than pilots flying with an egocentric frame of reference. The results of these five experiments seem to suggest that the exocentric viewpoint tend to support global judgments that are as good or better than the egocentric immersed displays.

Hypotheses and Proposed Experiment

The previous review has identified a number of studies that have examined the influence of the three features of VR (frame of reference, dimensionality, and stereo), on the four subtasks of visualization; however, most of these studies have involved navigation and judgments in an aerospace environment, adhering to the constraints on aircraft maneuvering, and flight paths, and the characteristics of the aerospace environment. Few have examined these influences in the unconstrained 3D "electronic space" of the virtual world. Hence, caution must be exercised in extrapolating the conclusions reached to the issues of data visualization in virtual environments.

Nevertheless, certain hypotheses may be voiced regarding which features will be more effective for which subtasks. In order to provide some concrete context for interpreting these hypotheses, we first describe briefly the paradigm

that we will use. Subjects will be asked to navigate through a 3D volume, filled with data points, visiting each point in turn. The desired target for a given leg will be specified by flashing, as soon as the previous target is encountered. The volume of points are not randomly distributed, but are configured to conform to a particular 3D volume or shape (e.g., surface, string, varied density, etc.). Periodically subjects will be probed regarding the specific position of certain objects and, after each configuration of data points has been traversed, subjects will be asked about its general form. Hence, we may characterize the task by its phases of search, travel, local judgments (object location), and global judgments (configuration description).

We anticipate that search will be facilitated by displays that can present the whole domain within view (exocentric and co-planar), and, on the basis of the study by Zenyuh et al., will be helped by stereo. The research from the aviation domain clearly predicts that TRAVEL will be best supported by the egocentric 3D display (Wickens and Prevett, 1995; Haskell and Wickens, 1993), whereas strong differences in favor of either the coplanar display, or the exocentric 3D display are not predicted, given the approximate equivalence of these two formats in prior research. Thus, we anticipate that the scanning costs of the co-planar format may be traded off against the ambiguity costs of the exocentric 3D format.

Predictions regarding local judgments are not strong either, given the possibility of these tradeoffs. Since all local judgments will be based upon objects that are visible in the forward field of view of the immersed display, and judgments involved "closest to," rather than "left-right," we do not have reason to predict a difference between the two 3D displays. We do hypothesize that 3D display judgments will be faster (because of reduced scanning), but less accurate (because of ambiguity), in contrast to the 2D displays.

Finally we predict a substantial superiority for the 3D exocentric display in terms of the support for global judgments of configuration shape. This display suffers neither the deficiency of keyhole viewing (of the immersed display), nor that of integration across panels (of the co-planar display). Wickens, Merwin, and Lin's (1994) finding of a 3D advantage for integration questions provides one empirical basis for the prediction of this superiority, in a paradigm using materials similar to that in the present experiment.

METHOD

Subjects

Thirty students at the University of Illinois (15 males and 15 females), all with normal or corrected to normal vision, served as voluntary participants. All of the subjects were paid $5.00 an hour for their participation.

Two groups for the between subjects manipulation of FOR were formed by assigning eight males and seven females to one group and conversely seven males and eight females to the other group. Other than the separation based upon gender, the assignment was completely random.

Apparatus and Displays

All subjects were required to execute a navigation task rendered in 3D space on a Silicon Graphics IRIS workstation. There were three displays perspectives used to guide the subjects in the 3D space; 2D, immersed and non-immersed. Figures 1, 2 and 3 show prototypical examples of the 2D, 3D immersed, and 3D non-immersed perspectives, respectively.

Initially all subjects were to participate in three types of trials, 2D, 3D monoscopic and 3D stereoscopic (for later subjects, the 2D condition was deleted for reasons that will be explained below). Stereoscopic viewing was produced by the use of Silicon Graphics Stereoview glasses.

Procedure

All subjects were instructed to navigate the 3D space as quickly and with as little joystick input as possible. The actual data environment was represented as a cube volume with six different colored walls. The volume, with 6 uniquely colored walls, contained a series of 15 major objects (destinations) along with 200 randomly placed smaller objects. The 15 major objects were defined within each cube to represent a particular 3D pattern. The description of this pattern was the goal of the subjects in the global judgment task.

The actual task required the subject to navigate the target icon. This icon was represented by a small arrow head symbol in one (3D) or both (2D) panels of the non-immersed conditions and by the display viewpoint defining the subject's field of view for the immersed condition. A joystick was used to make pitch and yaw adjustments. Constant deflection angles on either axis produced constant rate of change of yaw or pitch. Forward motion was induced by means of pressing the joystick button. This provided the motion capability necessary to navigate through the 3D space along a path orientated toward the flashing target cubes. A particular cube within the environment would flash, indicating its status as the

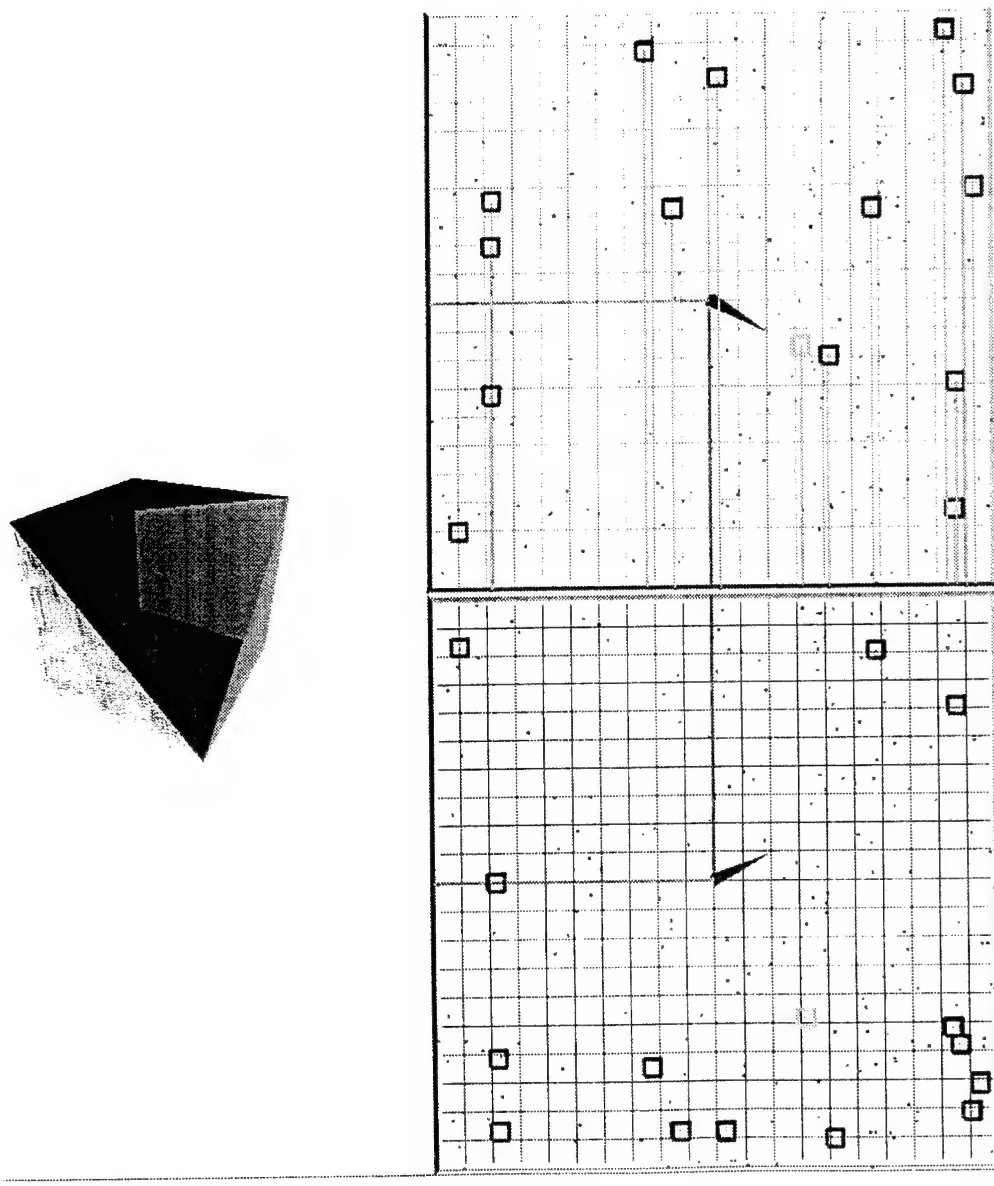

Figure 1. Example of 2D perspective.

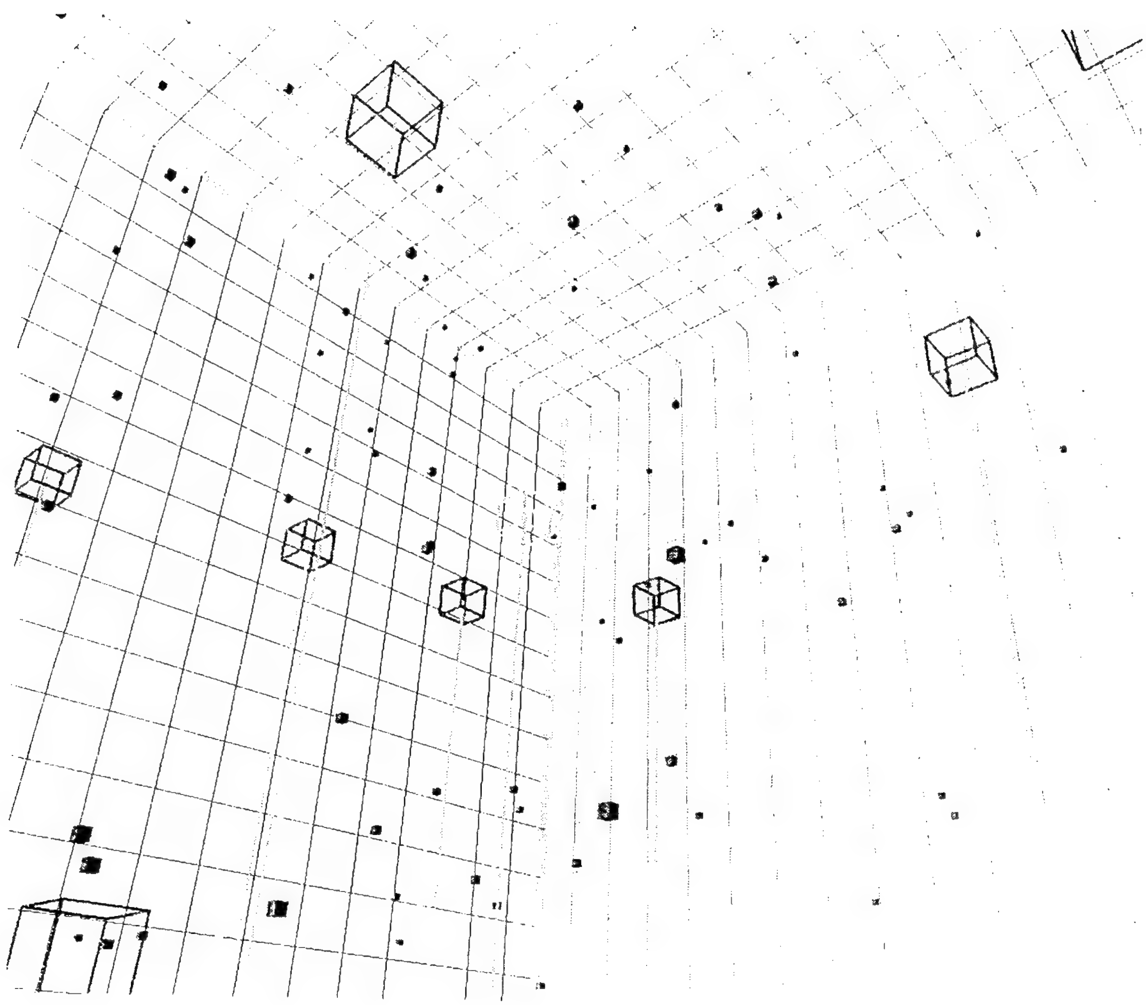

Figure 2. Example of 3D immersed perspective.

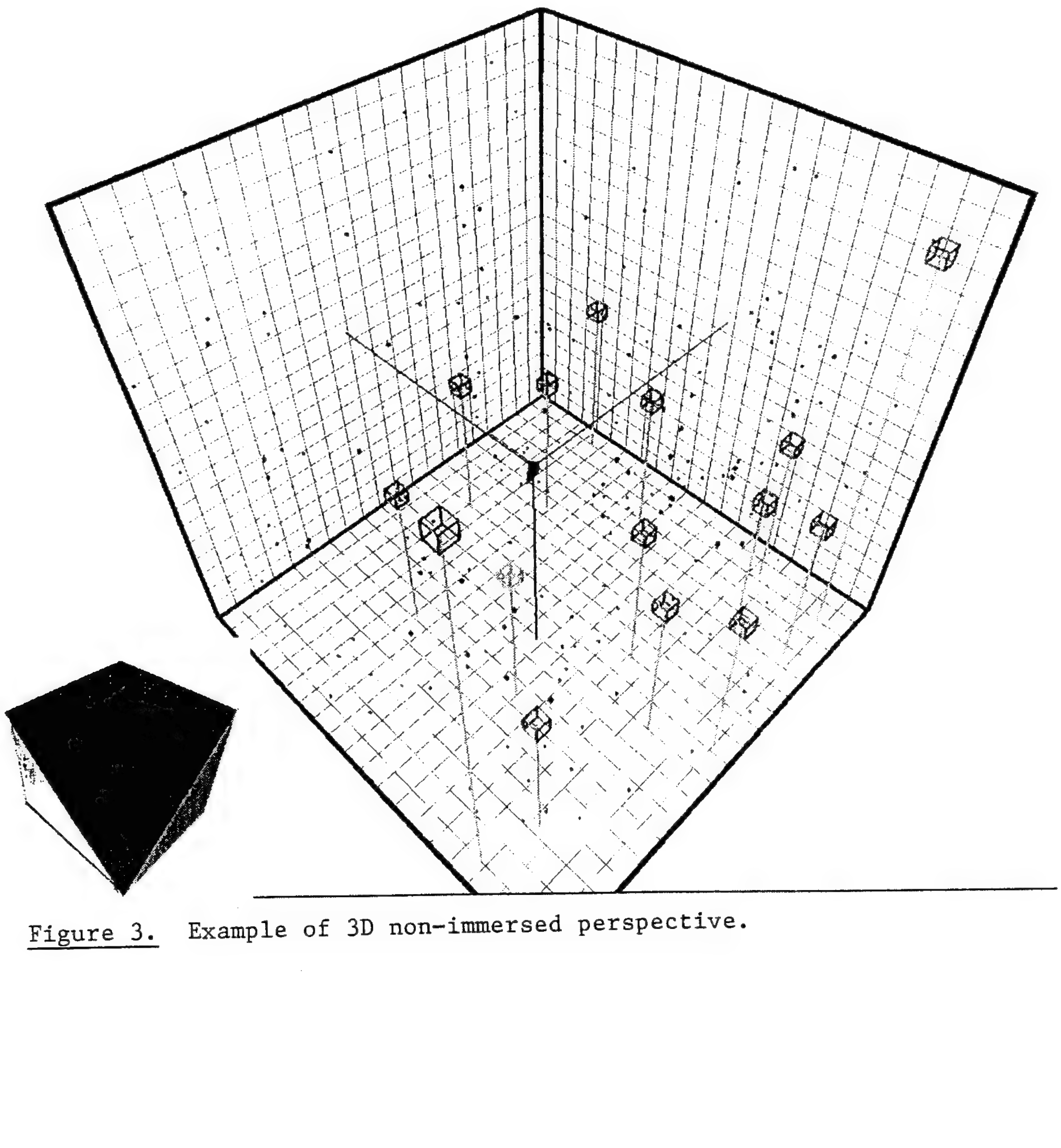

Figure 3. Example of 3D non-immersed perspective.

present target cube. After the subject successfully navigated the icon to intercept the target cube, its flashing would cease and a new target cube would begin to flash. Once search determined the location of the next cube, the subject would then orient and navigate the icon into the new target cube (recall that for the immersive conditions, search and orientation were done in parallel). Steering corrections could be made at any time (with or without forward movement). The program would automatically terminate that particular trial after interception of the 15th target cube. In this manner a complex 3D path, reaching all 15 targets, was traversed through the volume.

During each navigation trial the program would periodically halt to ask the subject to make a precise relative judgment of the location of an object within the current field of view (as defined for the immersive condition); identical questions were asked for the 2D and 3D non-immersive displays. This would take the form of a multiple choice question asking the subject which of the two objects was closer to his or her own position or to a certain colored wall.

Furthermore, after each navigation trial had been completed the program also asked a single multiple choice question to assess the subjects' knowledge of the global pattern or distribution of the particular data points just encountered. This assessment began by blanking out the entire screen and asking the subject a question regarding the general shape of the data base (e.g., position of target cubes, clumping of data points, or shapes formed by the collection of data points).

Experimental Design

Initially all subjects were to complete a total of 15 trials composed of 5 trials of each of the three possible perspectives: 2D split screen perspective, a monoscopic perspective and a stereoscopic perspective. The later two perspectives were represented in either an immersed or non-immersed frame of reference, depending on the experimental group to which a subject was assigned. A counterbalanced design created 6 possible orderings of the three possible representations and was used to reduce possible practice effects across trials.

Variables Measured

Data recorded for each subject consisted of actual navigation time for each trial, the accuracy and speed on both the relative judgment and global judgment questions, the average magnitude of joystick inputs required to find the next target, and the average magnitude of joystick inputs required to travel toward the next target. These inputs were measured in two ways. First, search inputs were defined as the amount of X and Y axis joystick movements recorded from the moment the craft intercepted the present target cube until the subject accelerated toward the next target cube. Secondly, travel inputs were defined as the amount

of X and Y axis joystick movements recorded from the moment the craft accelerated toward the next target cube until it penetrated the next target cube.

RESULTS

The analysis for this experiment could not proceed according to a mixed ANOVA model. This constraint is due to the fact that the design was not fully crossed. The frame of reference (FOR) viewing condition was not defined for the 2D condition and thus both FOR (immersed and non-immersed) subject groups used the same 2D displays to completed the task. Therefore, the analysis including the 2D condition was conducted separately from the stereoscopic vs. monoscopic analysis. For clarification, the first analysis consisted of a one way ANOVA which compared the three frames of reference against one another (2D, immersive and non-immersive), the latter two only within the monoscopic viewing condition. In terms of Figure 4, the FOR analysis for main effects compared performance in Areas 1, 2, and 4. As a continuation of the first (FOR) analysis, two Tukey post-hoc tests were conducted on any significant main effects. The first Tukey test used the standard alpha level of .05. The second Tukey test was aimed at finding marginally significant differences and used an alpha level of .10. In the write up of the post-hoc analysis all significant differences are at an alpha level of .05 and all non-significant differences are at an alpha level of .10.

The second analysis was a 2X2 design which analyzed the effects of stereoscopic viewing across the two frames of reference (immersed vs. non-immersed) in which stereo was manipulated. Due to the fact that the 2D condition was not included in the stereoscopic manipulation, this 2X2 analysis was not used

	Monoscopic Viewing	Stereoscopic Viewing	
<u>Area #1</u> 2D	**<u>Area #2</u>** Immersed & Monoscopic	**<u>Area #3</u>** Immersed & Stereoscopic	Immersed FOR
	<u>Area #4</u> Non-Immersed & Monoscopic	**<u>Area #5</u>** Non-Immersed & Stereoscopic	Non-Immersed FOR

<u>Figure 4.</u> Representation of experimental design.

to analyze frame of reference effects (The FOR analysis accomplished this), but was used only to analyze the effects of stereo across the immersed and non-immersed frames of reference. In terms of Figure 4, the effects of stereo were analyzed by comparing Areas 2, 3, 4, and 5. Both ANOVA's were analyzed using the Statistical Analysis Software (SAS) package.

Another modifying factor that affected the analysis of this experiment was the large number of subjects who withdrew during experimentation. The 2D display condition proved to be so difficult and confusing in some phases, that eight of the 15 subjects who encountered the 2D display withdrew from the experiment.

Seven subjects (5 males and 2 females) completed the 2D trials along with the other two conditions. Preliminary analysis of these subjects' results indicated that their performance was substantially worse in the 2D condition, especially in terms of time needed to complete the task. Therefore, the remaining 23 subjects were not assigned to perform the 2D trials.

The following sections present the results of this experiment in terms of the form visualization subtasks: Search, Travel, Local Judgment Support, & Global Judgment Support.

Search

Search performance is represented in terms of search time, X axis deviations, and Y axis deviations. These variables were affected only by dimensionality and frame of reference. There were no interaction between any of the variables.

Search time. The average time required to find the next target is shown in Figure 5 (note that there is a single data point for the two graphs in the 2D condition. This reflects the fact that only the mean value of the two groups is plotted. The first ANOVA (designated for FOR effects) revealed a significant main effect $F(2,4863) = 436, p < .0001$, indicating faster search for the non-

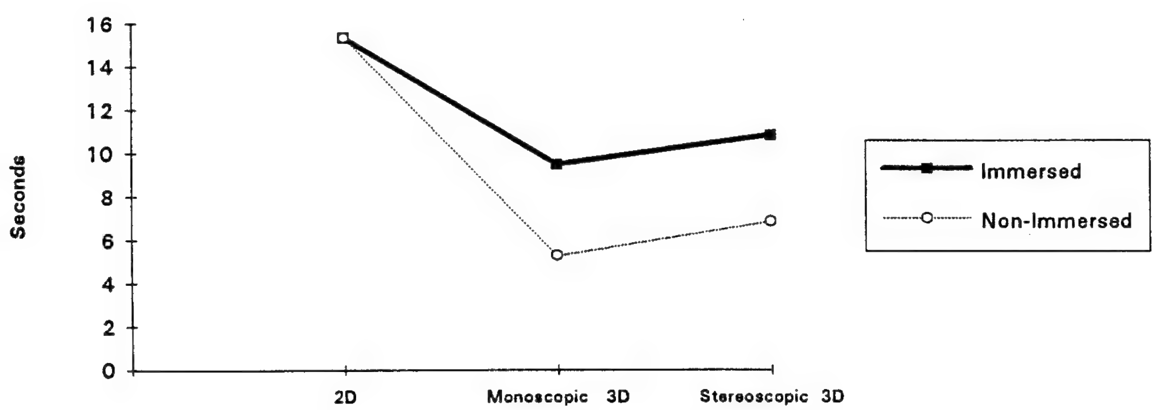

Figure 5. Average time during search.

immersive group. The FOR Tukey analysis indicated that the non-immersed condition had a significantly (200 msec) faster search time than the immersed and 2D conditions. Furthermore, the immersed condition was also significantly faster than the 2D condition. The second ANOVA (designated for stereo effects and examining areas 2 through 5) revealed that the non-stereo condition had a significantly faster search than the stereo condition $\underline{F}(1, 4423) = 50.48$, $\underline{p} < .0001$ (see Figure 5).

Search X-axis deviations. Average deviations in the X-axis are shown in Figure 6. The first analysis revealed a main effect of FOR $\underline{F}(2,4947) = 12.88$, $\underline{p} < .0001$, indicating that immersed viewing conditions had the highest X-axis deviations. The post-hoc Tukey analysis revealed that the immersed conditions had a significantly higher X-axis deviations than the non-immersed and 2D

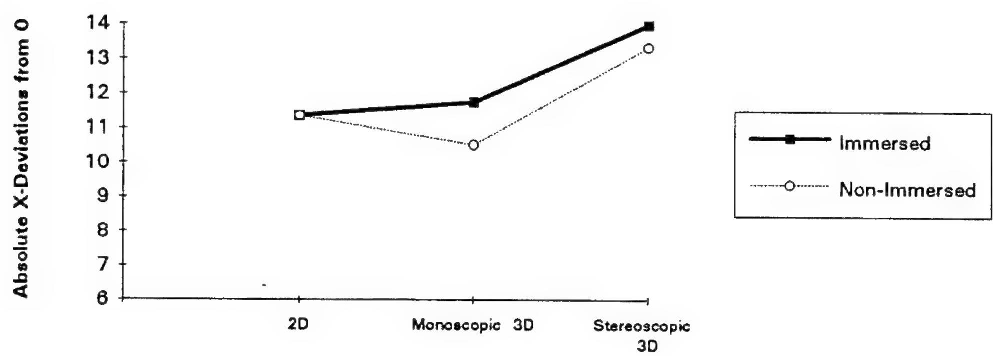

Figure 6. Average X input during search.

conditions. While the trend indicated that the non-immersed condition had higher X-axis deviations than the 2D condition, the difference was not significant. The second analysis revealed that stereo conditions had significantly larger X-axis deviations than did the non-stereo condition $\underline{F}(1,4498) = 128.44$, $\underline{p} < .0001$ (see Figure 6).

Search Y-axis deviations. The deviations in the Y-axis indicate a pattern similar to the x-axis deviations (see Figure 7). The first analysis revealed a main effect of FOR $\underline{F}(2,4941) = 59.29$, $\underline{p} < .0001$, indicating that immersed viewing conditions had the highest Y-axis deviations. The FOR post-hoc analysis revealed that the immersed conditions had a significantly higher Y-axis deviations than the non-immersed and 2D conditions. While a trend indicated that the 2D display had higher Y-axis deviations than the non-immersed display, the difference was found to be nonsignificant.

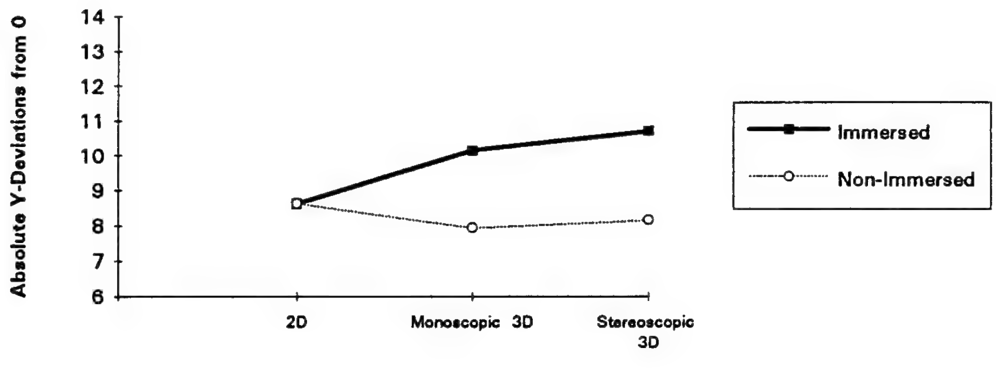

Figure 7. Average Y input during search.

The analysis for stereoscopic effects (see Figure 7) revealed a marginally significant (F (1,4495) = 3.02, p = .08) increase in Y-axis deviations for the stereo over the non-stereo condition.

Travel

Performance in successfully traveling from one target to another was measured in terms of travel time, X-axis deviations, and Y-axis deviations. While the Y-axis deviation measure was affected only by FOR and stereoscopic viewing, the time measure and X-axis deviation measures were influenced by a significant interaction between FOR and stereoscopic viewing.

Travel time. The average time required to travel from one target to the next is shown in Figure 8. The FOR analysis showed a main effect $F(2,4860) = 544$, $p<.0001$, indicating that the immersed viewpoint had the fastest travel times. The FOR post-hoc analysis revealed that the immersed condition had a significantly faster travel time than the immersed and 2D conditions. Furthermore, the non- immersed condition was also significantly faster than the

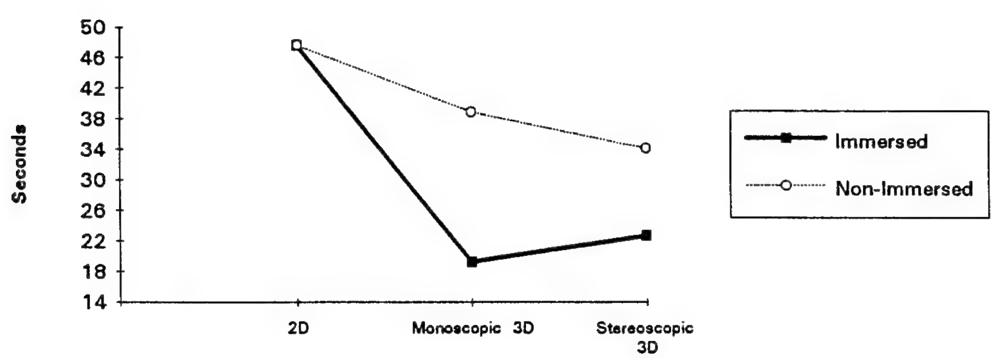

Figure 8. Average time during travel.

2D condition. The analysis for stereoscopic effects failed to show a main effect in travel time ($F = 1.35$, $p = .25$). However, this analysis must be considered within the context of the significant interaction between FOR and stereoscopic viewing ($F(1,4415) = 59.29$, $p < .0001$), which indicated that the benefits of immersion (to travel time) were diminished in the stereoscopic condition (see Figure 8).

Travel X-axis deviations. Average deviations in the X-axis during travel are shown in Figure 9. The repeated measures ANOVA of FOR showed a main effect; $F(2,4879) = 520$, $p < .0001$, indicating that immersed viewpoint had the smallest number of X-axis deviations. The FOR Tukey analysis revealed that the non-immersed condition had significantly higher X-axis deviations than the immersed and 2D conditions. Furthermore, the 2D condition was found to have significantly higher X-axis deviations than the immersed condition. The analysis

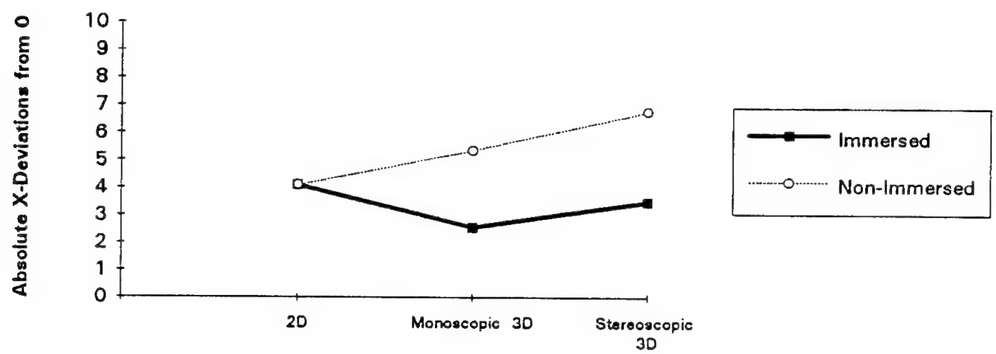

Figure 9. Average X input during travel.

for stereoscopic effects (see Figure 9) indicates a main effect, $F(1,443) = 126.57$, $p < .0001$, revealing that stereo conditions had significantly larger X-axis deviations. The significant interaction between FOR and stereoscopic effects, $F(1,4432) = 6.71$, $p < .009$, mediates the effects of both variables. Specifically, subjects using the non-immersed FOR showed a greater increase in X-axis deviations when using stereo than did those using the immersed FOR.

Travel Y-axis deviations. Average deviations in the Y-axis were recorded from joystick input during travel and are shown in Figure 10. The FOR ANOVA indicated a main effect of FOR $F(2,4902) = 149.25$, $p < .0001$, revealing that the immersed viewing condition had the smallest average Y-axis deviations. The post-hoc FOR analysis indicated the immersed condition had a significantly lower magnitude of Y-axis deviations than the non-immersed and 2D conditions. There

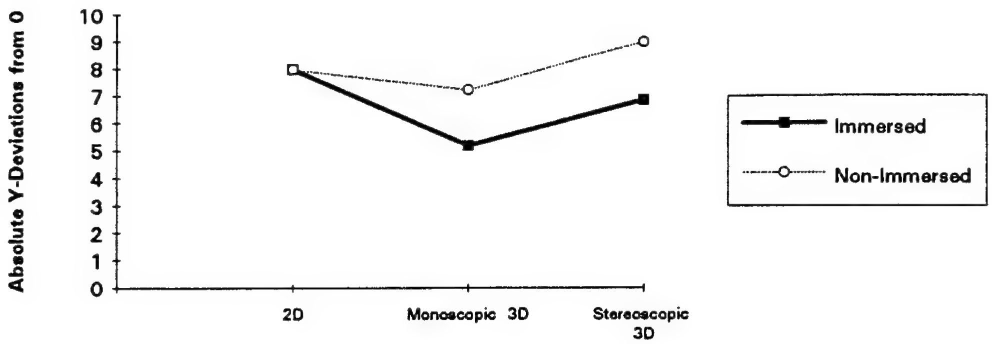

Figure 10. Average Y input during travel.

was no significant difference in Y-axis deviations between the 2D displays and the non-immersed displays. The stereoscopic analysis also revealed a main effect of stereo $F(1,4456) = 179.18$, $p<.0001$, revealing the stereo condition to have significantly higher Y-axis deviations.

Local Judgment Support

Local judgment accuracy. The average accuracy of local judgment tasks is shown in Figure 11. Since there were two possibilities for answers in the multiple choice questions used, chance accuracy was taken to equal 50% correct. The FOR analysis showed a main effect $F(2,327) = 28.90$, $p<.0001$, revealing that the 2D displays were the least accurate viewing condition. The FOR Tukey analysis indicated that the 2D condition had significantly lower accuracy than did the non-immersed and immersed conditions. There was no significant difference in

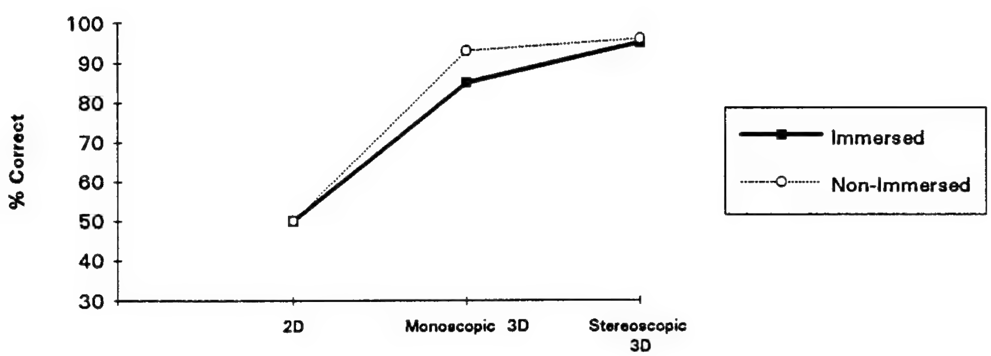

Figure 11. Accuracy on local judgments.

accuracy between the non-immersed condition and the immersed conditions. A similar analysis of stereo effects revealed that performance in the stereo conditions was significantly more accurate than in the non-stereo conditions $F(1,296) = 3.86$, $p< .05$.

Local judgment response time. Average times required to respond to local judgment questions are shown in Figure 12. The FOR ANOVA indicated a significant main effect $F(2,324) = 12.87$, $p<.0001$, revealing that the 2D displays had by far the slowest response time to the local judgment questions. The FOR post-hoc analysis revealed that the 2D condition was significantly slower than the non-immersed and immersed conditions. There was no significant difference in

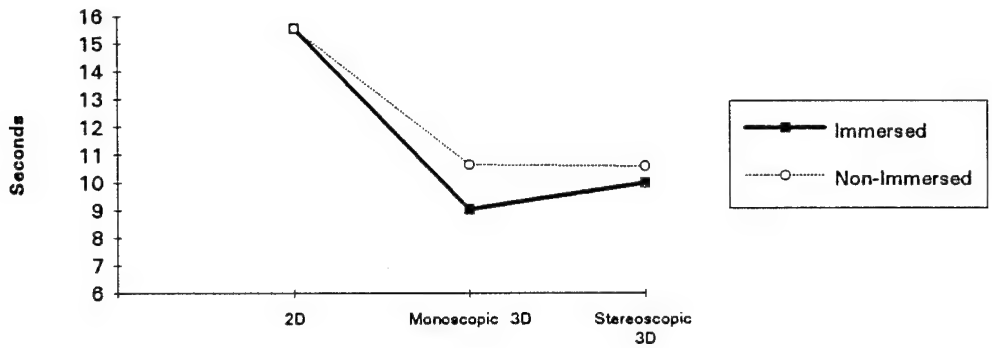

Figure 12. Response time on local judgments.

response time between the non-immersed and immersed FORs. The stereoscopic ANOVA revealed no significant difference between the two viewing conditions ($F = .44$, $p = .50$).

Global Judgment Support

Global judgment accuracy. Accuracy on the global judgment tasks is shown in Figure 13. Since there were four alternatives for each multiple choice question, chance accuracy is at 25% correct. The FOR analysis revealed a significant main effect $F(2,327) = 34.49$, $p<.0001$, indicating that the non-immersed displays had the highest global judgment accuracy. The FOR Tukey

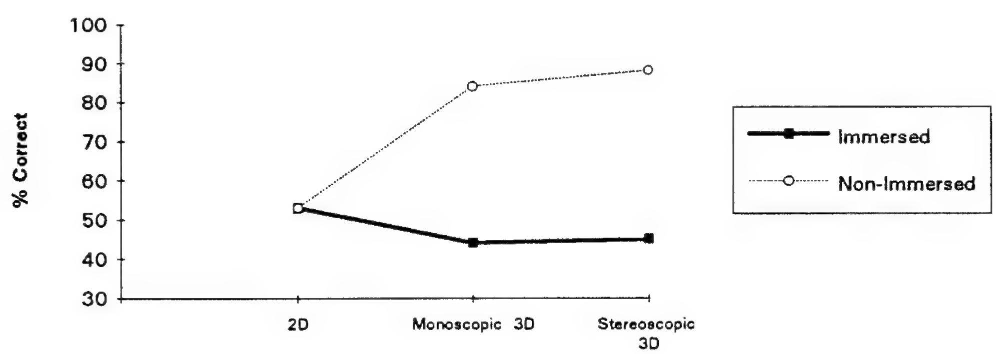

Figure 13. Accuracy on global judgments.

analysis indicated that the non-immersed condition had a significantly higher accuracy than did the 2D and immersed conditions. There was no significant difference in accuracy between the 2D displays and the immersed displays. The stereoscopic ANOVA revealed no significant difference in global judgment accuracy ($\underline{F}$ = .29, $\underline{p}$ = .59).

Global judgment response time. Average times required to respond to global judgment questions are shown in Figure 14. The FOR ANOVA revealed no significant main effect ($\underline{F}$ = .97, $\underline{p}$ = .38). The stereoscopic ANOVA revealed

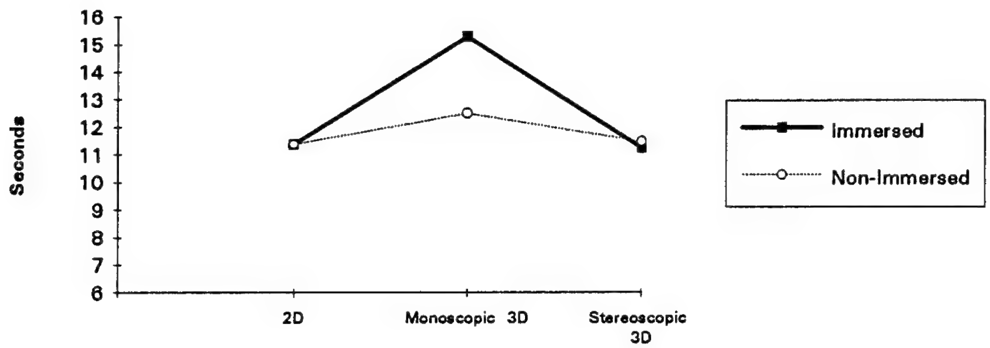

Figure 14. Response time on global judgments.

stereoscopic viewing to promote significantly faster response times than did non-stereoscopic viewing $\underline{F}(1,285) = 5.45$, $\underline{p}<.02$.

DISCUSSION

The present experiment was intended to examine three "features of virtual reality" (Wickens and Baker, 1995) in an effort to assess the extent to which these could contribute to effective visualization of a 3D volume of data, characteristic of that confronted by the geologist who wishes to assess the nature and configuration of toxic deposits. The three features, display dimensionality, frame of reference, and stereo viewing have each been examined in a wide variety of different task environments. Several studies in particular have examined combinations of these features in aviation-relevant tasks, and their results have some relevance for interpreting the present data. However, missing from most empirical studies in the visualization area are the combined manipulations of these features in a <u>dynamic interactive environment</u>, while operators perform a task, whose assessment characterizes success in understanding the structure of the data.

In our discussion, we shall consider these three features of virtual reality in turn, as they are expected to influence performance on four tasks characteristics of users of virtual environment technology: <u>search</u> for important objects, <u>travel</u> to those objects, rendering <u>judgments</u> about <u>local features</u> in the environment, and most important, rendering <u>judgments</u> about the <u>global</u> or "holistic" <u>configuration</u> of data points within the environment (e.g., are they arranged in a clustered pattern, are they correlated across dimensions of space, etc.?).

<u>Dimensionality</u>. The effect of dimensionality was most noteworthy and prominent. Across all tasks, the best 3D display always supported better performance than the 2D coplanar display, and the poorest 3D display (which as we saw, was task-dependent), was never substantially worse than the 2D display.

In the several studies comparing 2D and 3D displays that we have carried out in our lab involving aviation, air traffic control, and data visualization (e.g., Wickens, 1995; Wickens, Merwin, and Lin, 1994; Wickens and Prevett, 1995; Olmos, Liang, and Wickens, 1995; Wickens, Liang, Prevett, and Olmos, 1995; Boyer et al., 1995; Wickens, Campbell, Liang, and Merwin, 1995; Haskell and Wickens, 1993), this is the strongest and most consistent 3D advantage that we have ever found. The reason for this advantage can be attributed to the current task which truly forced integration across all three axes of the data volume -- that is, both the distribution of data points (and therefore judgments on those data points) as well as the requirements for travel, involved an equal mixture of Δx, Δy, and Δz. This circumstance is in contrast to many aspects of aviation and air traffic control, in which the pilot and controller both have reason to treat the lateral aspects of flight differently and separately from the vertical aspects, both in terms of perceptual judgments and control strategy. Such partitioning has been found to lead to advantages for separated coplanar displays (Haskell and Wickens, 1993).

In the absence, in the current data, of any explicit advantage for a coplanar display, the two important costs of this display configuration emerged: the visual scanning required between the two display panels, which accounts for the prominent 2D slowing of many task components, and the "mental gymnastics" required to integrate movement and position on the two displays in order to discern 3D patterns and trajectories.

These results, in short, are quite consistent with the proximity compatibility principle described by Wickens and Carswell (in press), that the task of integrating across axes is best served by a display which provides some degree of integration in the spatial depiction of those axes (see also Haskell and Wickens, 1993; Wickens, Merwin, and Lin, 1994 for corresponding results in aviation and data visualization, respectively).

Frame of reference. The difference between the immersed, ego-referenced 3D view, and the exocentric stabilized field of view provided evidence for prominent tradeoffs between tasks, evidence which has been observed in other studies in aviation (c.f., Wickens, Liang, et al., in press; Wickens and Prevett, 1995). In particular, we noted these tradeoffs in three aspects of performance, each of which can be accounted for by different information processing mechanisms. First, search was disrupted by the ego-referenced frame, a disruption we attributed to the "keyhole" phenomenon associated with the relatively narrow GFOV provided by this display. Since the whole domain is not in view at any given time, then looking for a target not present on the display, is akin to swinging a wide beam flashlight around the space -- far less efficient than a search driven by visual scanning, characteristic of the non-immersed display. The added difficulty of the egocentric search caused by the keyhole is evidenced by the greater amount of control movement observed during the search phase processing. Of course with the egocentric display, once the target had been found, the orientation phase was already completed, whereas this still needed to be accomplished with the exocentric display. But this benefit was obviously small, relative to the "keyhole cost," leading to a net loss of several seconds in immersion search performance.

In contrast, as a second example of the tradeoff, performance during the travel phase clearly benefited from the egocentric FOR, a finding well replicated in flight tasks (Wickens and Prevett, 1995; Barfield et al., 1995). We suggest four possible reasons for the immersion benefit to travel: (1) when the axis of control rotation corresponds with the display viewpoint (the immersed display), a certain natural or "ecological" compatibility is achieved, which readily supports ego motion (Warren and Wertheim, 1990); (2) the immersed view, traveling through the object-populated world provides the user with a very salient sense of ego motion from the "flow field" of objects streaming passed the viewpoint. This optical flow, a cue of assistance for travel (Larish and Flach, 1990) is, of course, missing from the exocentric view; (3) the exocentric view suffers to some extent from ambiguity along the line of sight; that is, judgments of precise location along

the viewing axis, relative to the target cube are difficult when the user's icon is close to the cube; and (4) a final source of exocentric cost probably relates to the fact that we chose a static view point. This meant that on trajectories moving back toward the viewer, what movements that were to the left on the display required rightward corrections on the control and vice versa. That is, either a control reversal strategy, or some form of mental rotation was required for control in this direction, features that we have established to be clear sources of difficulty with fixed map displays (Aretz and Wickens, 1992; Wickens, Liang, Prevett, and Olmos, in press), and probable sources of the added (less efficient) control activities observed with the exocentric display.

Turning to the two judgment tasks, we found a modest, but reduced (2 secs) immersion benefit to local judgments time, but no advantage for accuracy (in fact, there was a nonsignificant 10% loss). Such judgments were not of course hindered in the immersed view by keyhole effects, since the requested attributes were always visible on the display panel. In contrast, for the task that may be thought of as most critical for data visualization -- the recall of global configuration -- the exocentric view realized a substantial advantage in both the time and the accuracy of response. In this regard, our results were quite consistent with those of Wickens and Prevett (1995) who also found exocentric advantages to measures of spatial awareness. However, we attribute the source of this advantage to a somewhat different mechanism than that inferred by Prevett and Wickens. We consider in the current study that the difficulties with global awareness resulted from problems with forming a "mental picture" of the configuration from several sequential keyhole views (not unlike the 2D-3D effect on global awareness: 2D requires integrating views separated in space, not time). This challenge was not the cause of the deficiency observed by Wickens and Prevett, since the GFOV in their display was always adjusted to be the same for immersed and nonimmersed views.

Stereo effects. The presence of stereo viewing conditions has been found, in past research, to aid depth and distance judgments by augmenting the impoverished depth cues along the LOS (Wickens, Todd, and Seidler, 1989; Yeh and Silverstein, 1992; Sollenberger and Milgram, 1993). Such evidence was provided here when stereo was found to assist conditions that suffered from ambiguity -- in particular, the cost of travel in the 3D exocentric viewing condition, and the accuracy of local judgments for both 3D conditions.

Equally important was the information provided by the present data, regarding where stereo was not helpful. First, it provided no benefit to search performance. This contrast with the results observed by Zenyuh et al. (1988) can be easily explained by the fact that for these investigators, the target attribute was defined, in part, by the very depth axis which stereo helped to resolve. This was not the case in the present experiment, since the targets were defined by an attribute -- flashing -- that was unrelated to depth.. Second, stereo provided no

assistance to immersed travel. This finding is consistent with the observation made by Nataupsky and Crittenden (1988) using a flight control task, that stereo offered no benefits to an ego-referenced "tunnel in the sky," when that display contained other rich cues for depth, distance, and ego motion judgment. Indeed these results are consistent with conclusions drawn from their review of the literature by Wickens, Todd, and Seidler (1989): when ample depth cues are available from motion parallax (as they were here in the ego, but not the exocentric displays), the addition of stereo cues offers few, if any, benefits.

Conclusions. Collectively, we may ask how these results speak to the importance of the three features of VR for data visualization. In making such an evaluation, we can consider two characteristics, the relative importance of each of the four subtasks to the full visualization objective, and the ease of automating these tasks by other means.

In this regard, we argue that search and global judgments are probably most critical. Furthermore, neither of these subtasks can be readily automated because the scientist does not always know what she is looking for (search) till it has been found, and of course, assessment of global configuration is often the goal of irreplaceable human insight.

On this account, the exocentric display, augmented where necessary by stereo, is clearly the display of choice. The one task in which the egocentric immersed display excelled is one that is not necessarily that important for interactive data visualization. It may be regarded as a means to an end, rather than an end itself. Furthermore, travel is a component that may be automated with relative ease: the user can identify the desired destination of travel (e.g., by positioning a cursor on the target), and then allow the computer to "fly " such a trajectory. Finally, it should be noted that the exocentric display used in this study contained an element -- the fixed viewpoint -- which we know to inhibit navigational travel (Wickens et al., in press). It may well be that if the viewpoint is altered so that it is "tethered" behind the icon, still retaining the full space in view, then the exocentric deficiencies of travel will be eliminated. This option is the subject of current research.

CONCLUSIONS

Summarizing the findings of this work, we found that the best performance for search and understanding or comprehending 3D data sets should come from 3D displays using an exocentric frame of reference. Furthermore, we found that augmenting the 3D exocentric displays with stereo provides the ideal combination of accuracy and speed for scientific visualization judgment tasks. However as we mentioned earlier, scientific visualization has another component that must be addressed: Database navigation. The exocentric FOR, even with the augmentation of stereo, still will require support to overcome line of sight ambiguities.

However. there are some possible solutions to the navigation problem that deserve future consideration. The first may be a viewing option allowing the user to alternate between egocentric and exocentric frames of reference. This would allow the user to choose the FOR, either egocentric or exocentric, best suited for the particular purpose (navigation or supporting understanding of the environment respectively). Another option would be to tether the user's viewpoint behind the controlled icon (Barfield, Rosenberg, & Furness, 1995; Wickens & Prevett, 1995) so that the viewpoint is always egocentricity oriented. This tethering would present the user with a more exocentric view of the environment, which would support better global judgments. However the tether would align the icon in a fixed position behind the icon, thus allowing the user to follow the icon and removing much of the 3D ambiguities of exocentric viewing as well as mental rotation problems. The final option could be to designate a point destination (i.e., "clicking the point" with a mouse or other input device) and allowing an "autopilot" to bring the icon to it. This would remove the user from the tracking process altogether, and allow the user to devote her or his attention to the task of perceiving and understanding the environment.

However in terms of this research, due to the great importance that search and global judgments have in data visualization, a scientist examining data points within a 3D volume would best be served by an 3D exocentric display that visually presents the entire 3D volume under scrutiny. This exocentric display would allow the scientist faster searches (locate and orient) for particular entities and more accurate global judgments than would be possible with the 2D displays and the "key hole" view created by the 3D egocentric display. Furthermore, the scientist should not use stereoscopic viewing during the search phases, due to its slowing effects. However, the scientist would benefit from stereoscopic viewing on global judgment tasks. Therefore, a viewing option allowing the scientist to alternate between stereo and monoscopic viewing might be ideal.

This research supports the viewpoint, suggested in the Introduction, that more reality will not necessarily lead to better performance. The driving force behind visualization is to present data visually in a way that allows the scientist to

obtain insight regarding the data. While VR will most definitely have an important impact on many fields of science, we feel that a complete application of all features of VR to the field of scientific visualization would be an over extension. Proper applications to scientific visualization must be guided by empirical studies which analyze the specific effects of the individual components of virtual reality.

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